When You Can't Beat 'em, Join 'em:

Leveraging Complexity Science for Innovative Solutions

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Current Problem Domain

- Commander’s intent: Networked Navy & the intent of CYBERSAFE
  - Cyber threats = lack of resilience for SoS, networks.
  - Weak links on autonomous vehicles
  - Challenges with large scale ad-hoc battlespace networks
- Needs:
  - Dynamically adaptable cyber resilience
  - Threats may use autonomous (e.g. machine learning) adaptation.
  - Collective behaviors, e,g, swarms.
  - Novel approach may need novel mathematics as foundation.
  - Fundamentally, a complex adaptive system.

Historical Problem Domain: Net-Centricity and its Problems

- Books by Moffat, Alberts, published 2000-2003 describe aspects of the Net-Centric Battlespace needed for NCW (Net-Centric Warfare):
  - Has attributes of self-similarity (fractal nature)
  - Involves thousands of entities (network nodes)
  - Answers may lie somewhere within complexity science / chaos theory
- A solution would need:
  - Adaptive dynamic behaviors for resiliency
  - Scale upwards at least several orders of magnitude
  - Be computationally tractable
  - Converge to solution in short timeframe (milliseconds to a few seconds)

Fields of study and their overlap

Complexity Science: deterministic / non-deterministic chaos

Autonomy	• A.I./M.L. • Emergent attributes
Architecture & Topology	• Hierarchical • Self-similar (Fractal)
Cyber	• Resilience • Adaptability

What shaped my perspective on tackling the problem

- Physics undergrad, software engineering jobs in comms, video games, robotics
- Started NAWCAD (NADC) as a computer scientist / engineer researching Neural Networks (NNs) and mathematical modeling of physical & biological phenomena
- A.I. Branch – broadened my focus on machine learning, also had opportunities to apply NNs to real-world Navy problems
  - **Noticed need for distributed architectures & emergent phenomena**
  - **Leveraged fractals and chaotic systems for advanced NN prototypes**
  - **Deep dive on chaos & complexity science.**
- Modeling & Simulation (DFS Centrifuge) developed expertise in distributed networks and graphical software
- Private start-up “big data” focus, was director of research focused on semantics, fractal topologies and genetic algorithms
- M&S –ACETEF, software, specific focus on algorithms
- 2010-now: cyber engineering, autonomy & Machine Learning, advanced architectures

What is complexity science?

- Complexity science is informally known as ***order creation science.*** Novel coherent properties can result from self-organizing System of Systems (SoS). Collective actions of many entities in a system produces *emergence*.
- **There are various methods to create complex SoS and emergence, for example:**
  - New approaches in computational (experimental) mathematics for multi-agent systems.
  - Deterministic chaos (fractals).
  - Pecora & Carroll's research on information embedded below chaotic noise threshold, similar chaotic circuit can "decrypt" signal from noise.
- **Application Focus**: Cognitive robotics incorporates the behaviors of intelligent agents within the shared world model.
  - Multi-agent systems create challenges for desired behaviors within a planned environment due in part to the problem of translating and using symbolic reasoning for world abstractions.
  - Even the lowest level distributed C2 (Command & Control) comms can produce complexity.

Emergent Behavior: what is it?

- Emergent behaviors result ***not*** from stochastic (e.g. thermodynamics) models, but instead from multi-agent interactions (e.g. RoboCup).
- Emergence can produce 'creative' system behaviors.
- Artificial Life - uses emergence generating algorithms:
  - genetic algorithms, neural nets, cellular automata.
    - E.g. "The Sims" uses genetic algorithms for automata.
- Emergent SoS ***cannot*** be designed by functional decomposition.
- Nonlinear systems: Can they have predictable behavior?
  - Predictability 'collapses' as sequence progresses (complexity increases).
  - Chaos can result from even small changes.
  - Known initial and intermediate conditions can have unpredictable results = Emergent behavior.

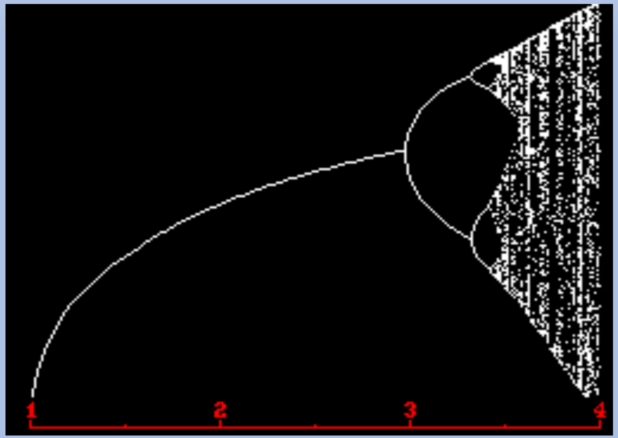
Why should we use complexity science & how?

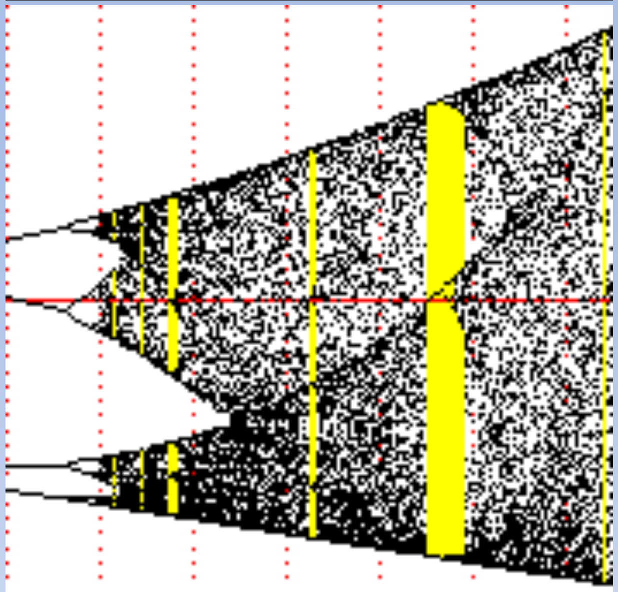
- Why?
  - Systems engineering is limited by its current System of Systems (SoS) approach to consistently predict novel / **emergent** behaviors that would give the U.S. an edge on our adversaries.
  - Large-scale multi-agent SoS, which are complex systems, typically show emergent behaviors.
  - Collective actions of many entities in a system produces emergence.
  - Complexity can provide a solution to translating the world into actions, by bounding the behaviors of distributed agents to produce new (emergent) and desired collective behaviors.
- How?
  - System elements need to be more adaptable, loosely coupled, and create a dynamically interoperable environment.
  - Complexity science is better modeled by using a localized, connectionist ontology of heterogeneous agents than by using equilibrium models from thermodynamics.
- Novel coherent properties can result from these self-organizing systems

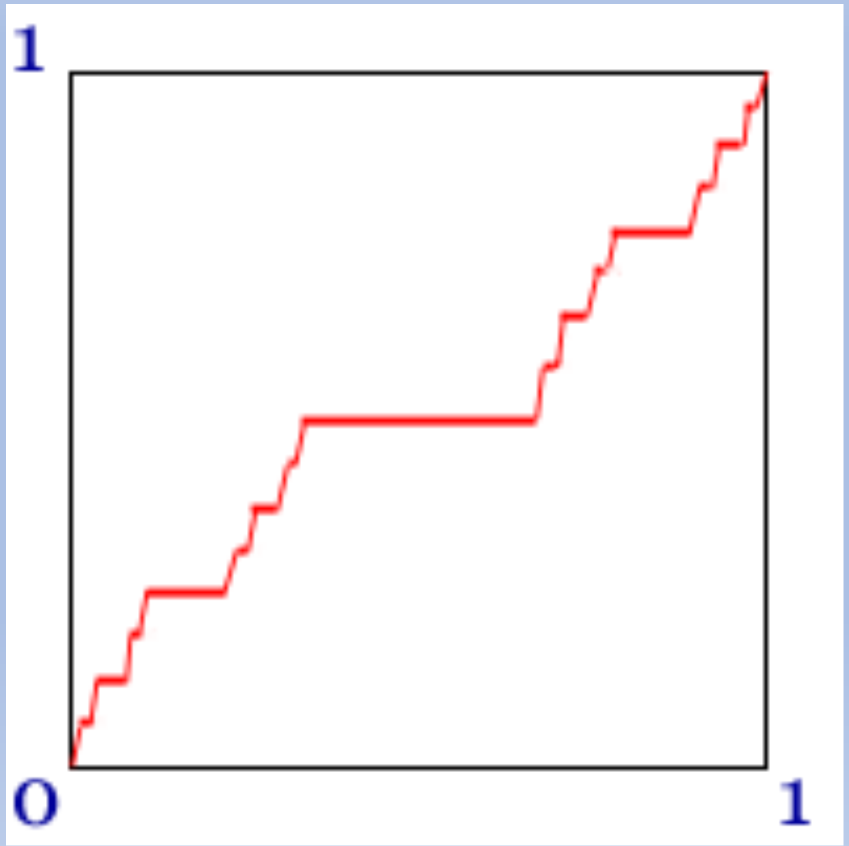
What is a Complex System ?

- Consists of many components associated by structure or just abstract relationship.
- May be scalable and self-similar at more than one level.
- Not described by simple rule or from the fundamental level. Predictable parts can form unpredictable system behavior.
  - E.g.Mandelbrot (fractal’s inventor): “transmission line noise” appeared random, was predictable “Cantor Dust”.
  - Bifurcation - “Feigenbaum diagram” at phase transitions (solid/liquid/gas), etc. represents nonlinear dropoff.
  - Devil’s staircase – at phase transition = chaos.

Diagrams: Feigenbaum and Devil's Staircase







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Complexity in Other Realms

- Most body functions exhibit complex behavior - fractal pattern of heartbeat, ionic channels, etc.
  - when ECG pattern becomes *less* complex, then indicates potential heart problem !!
- Chaotic (complex) chemical reactions:
  - Belousov-Zhabotinskii reaction (color change)
- Can even build an electronic circuit with complex behavior - can be driven to chaotic
- ***Can we control chaos?***

Chaos rules!

Chaos Prevails by Speg of the Pigs (2014) https://www.flickr.com/photos/write4nothing/15404507019/
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Wait…what? Chaos is good???

Generalized conjecture on chaos:

- Simple deterministic or even random stochastic models may not be the answer in our quest for human-like behaviors, or even the self-organizing patterns that occur in nature
- Perhaps we should look to controlling chaotic phenomena, as nature does, for the discovery of emergent patterns. This may lead to solutions for self-organizing large scale networks, or even human-like behavior in robots

Self-Organizing Complex Systems: Chaos Under Control

- Artificial biological systems:
  - Neural networks, Genetic algorithms, Boolean nets (Kauffman), Cellular Automata (Wolfram).
- Real biological systems:
  - Civilizations, economies, evolution (Kauffman), biological organisms, cognitive thought process.
- Experimental mathematics:
  - A "new" type of mathematics, previously unexplored due to computational limitations of the past.
  - ***Not*** Formal Methods, and no available proofs.
  - May depend upon deterministic chaos.

Control of chaos – *an example*

Problem: Spatially distributed large dynamic networks:

- Lose edge node communications.
- *Congressional Research Report (2007):*
  - Scaling limitations for large numbers of battlespace networked nodes.
  - Combinatorial explosion from massive numbers of route calculations.
- To increase *availability and resiliency* in network-centric clouds and swarms, ad-hoc nodes must rapidly self-organize using shared topology data.
- Topology can affect network **failures** and **success** of cyber offense and defense.

Perhaps we can leverage complexity science for a solution:

- Moffat's 2003 paper titled "Complexity Theory and Network Centric Warfare" referenced complex systems and their relationship to fractals and decentralized NCW.
- High volume network traffic packets self-organize to fractal (Leyland et al., 1994), therefore fractal may increase availability for large networks.
- Use a fractal that can adapt to needed topology.

Adaptive fractal experimental math discovery: an outgrowth of the linear chaos game

Like the simple point-slope equation for line:

- Deterministic chaos equation is **X(n) = M*X(n-1) + Z.**

X(n-1) = ***current point,*** **X(n)** = ***next point***.

Z: "vertices" = a set of initial points that constrain all node points, can represent network hubs. ***Z*** *is* ***randomly*** *selected* out of this set.

M: scale parameter = controls where the ***next point*** *is generated* from the ***current point***. $0<|M|<1$.

Both variables **M** and **Z** share interdependencies that affect the overall network topologies, including thresholds for clustering and the mappings to certain cluster elements.

Naming the algorithm and using the results

<u>Algorithm Name:</u> Non-predetermined Parametric Random (NPPR) Iterated Function System (IFS)

<u>Running it:</u>

- Node and hub considerations:
  - Points plotted show distribution of network nodes; ***<u>vertices = hubs</u>***.
  - Hubs may be virtual, i.e. location for calculation purposes only, and can add, move, delete.
  - Nodes know relative layout of clusters, coalesce around hubs for communications clusters.

<u>Results:</u>

- Combinatorial explosion and cyber impact avoided by use of NPPR.
  - Usually is an issue in large ad-hoc networks (Adams & Heard, 2014).
- NPPR topology is *information-dense:* a little info can reconfigure network.
  - Hub changes broadcasted as lat/lon position.
  - Scale parameter changes from chaos to order.
- Produces repeatable macroscopic results, even with unique node positions
  - Can apply to large-scale swarm control, adaptive cyber warfare.
  - Shared *stigmergic* knowledge by all nodes – i.e. each knows position of "neighborhoods"

Attributes of this solution

- Solution is:
  - Self-similar – each node can “know” the topology relative to other nodes
  - Facilitates situational awareness for tens of thousands of distributed nodes
  - Uses Deterministic Chaos
- Solution has:
  - **Adaptive fractal topology** with dynamic behaviors for resiliency
  - Fractal **self-similarity** can scale upwards many orders of magnitude
  - **Linear equation** = like point-slope equation of line is computationally tractable
  - Converges to solution in short timeframe in 10-100 millisecond timeframe
  - Exhibits stigmergic behaviors
- **This is but one possible solution out of many, that can be discovered by using computational (experimental) mathematics**

Personal Consequences of this Research

- Used as my successfully defended dissertation topic
- Discovered interesting emergent behaviors in a simple equation
- Received 2015 Outstanding Workforce Development Award as a direct result of this academic research project
- Wrote a chapter for engineering book on Engineering Emergence

Screen layout of NPPR “tool”:

A = Slider controls size (# pixels) in node-points plotting window, at bottom.

B·= Hubs topology map, used to drag-and-drop a hub relative to others, or create hubs.

C = Resets diagram to a default 3-vertex, 0.5 scale for equilateral Sierpinski gasket.

D = Checkbox that toggles display of horizontal and vertical axes.

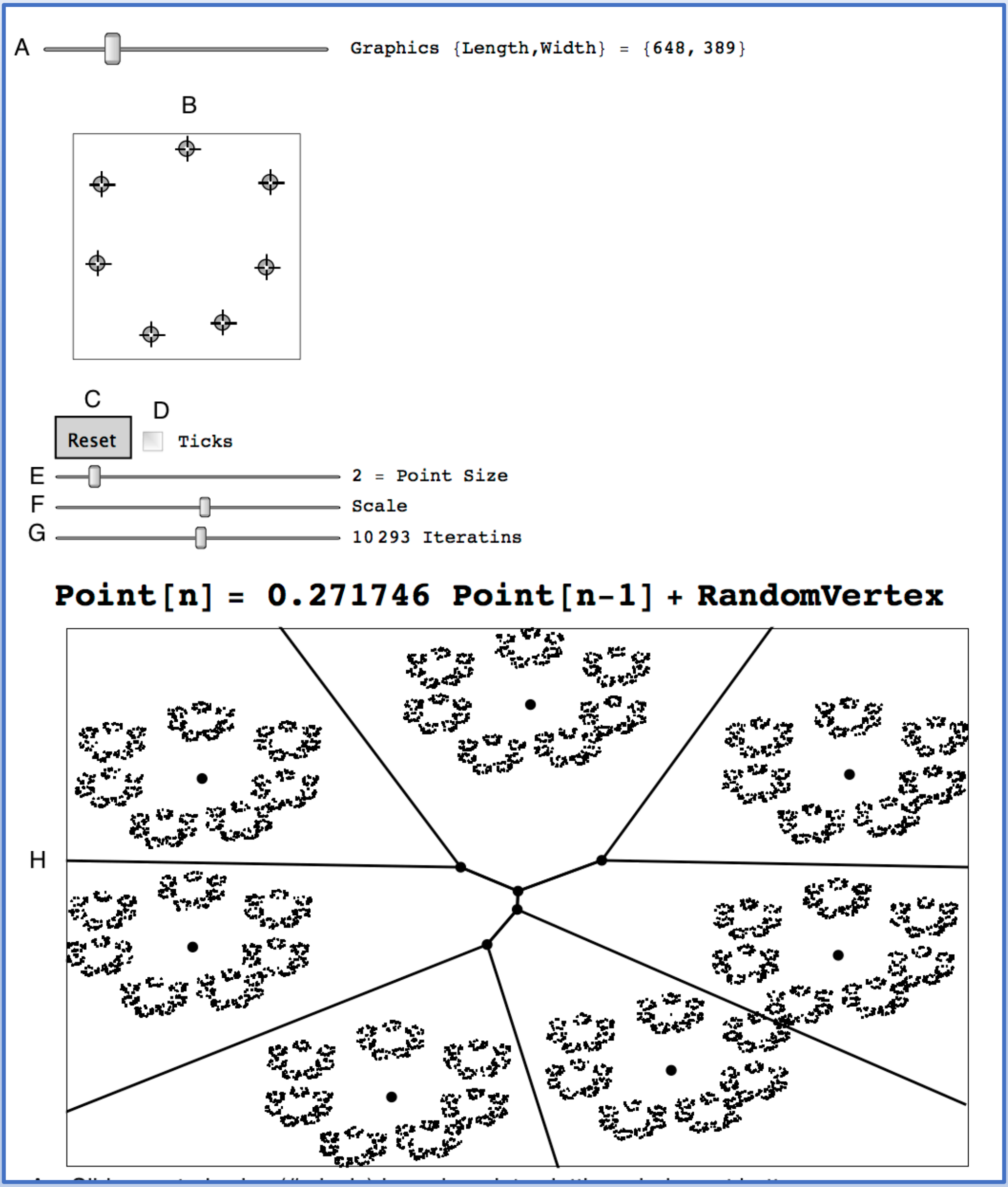
E = Slider for number of pixels selected to represent each node plotted.

F = Scale slider for the NPPR parameter (floating point multiplier).

G = Slider for the total number of points (nodes) to plot.

H = Lines indicate Voronoi partitions, for cluster observation guidance.

I = Nodes plotted using formula at top of window. Center points correspond to hubs.



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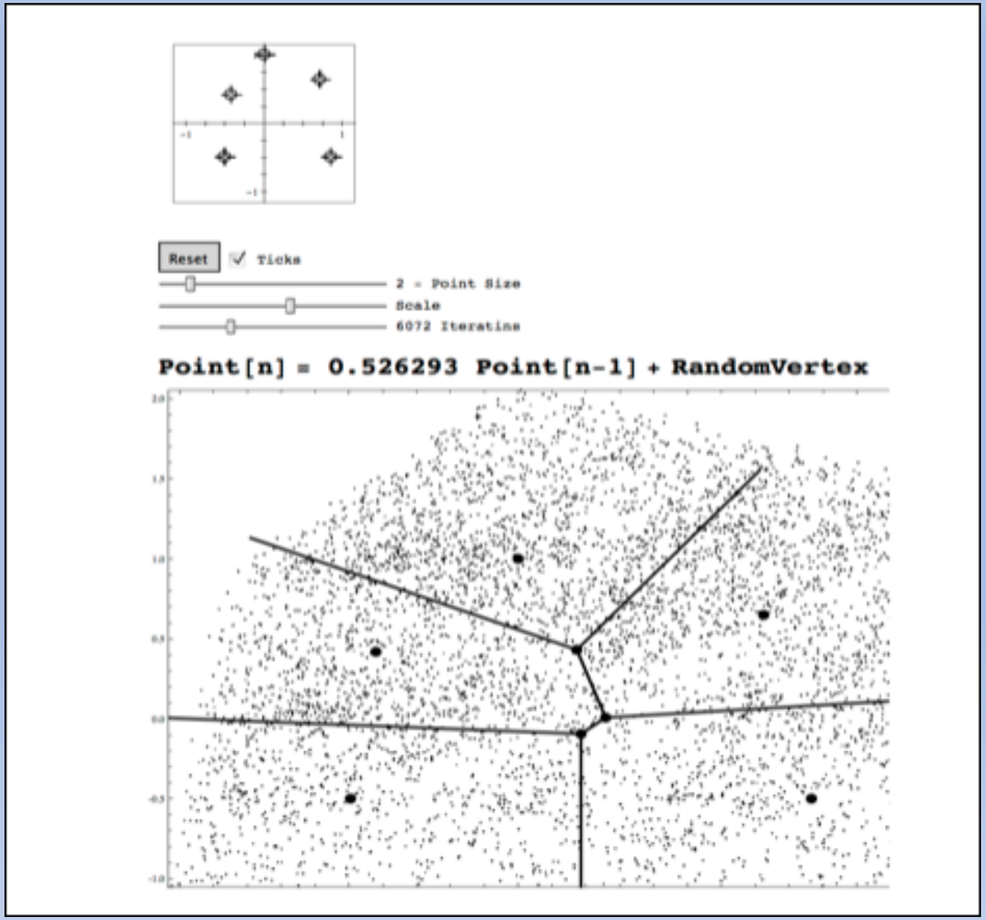
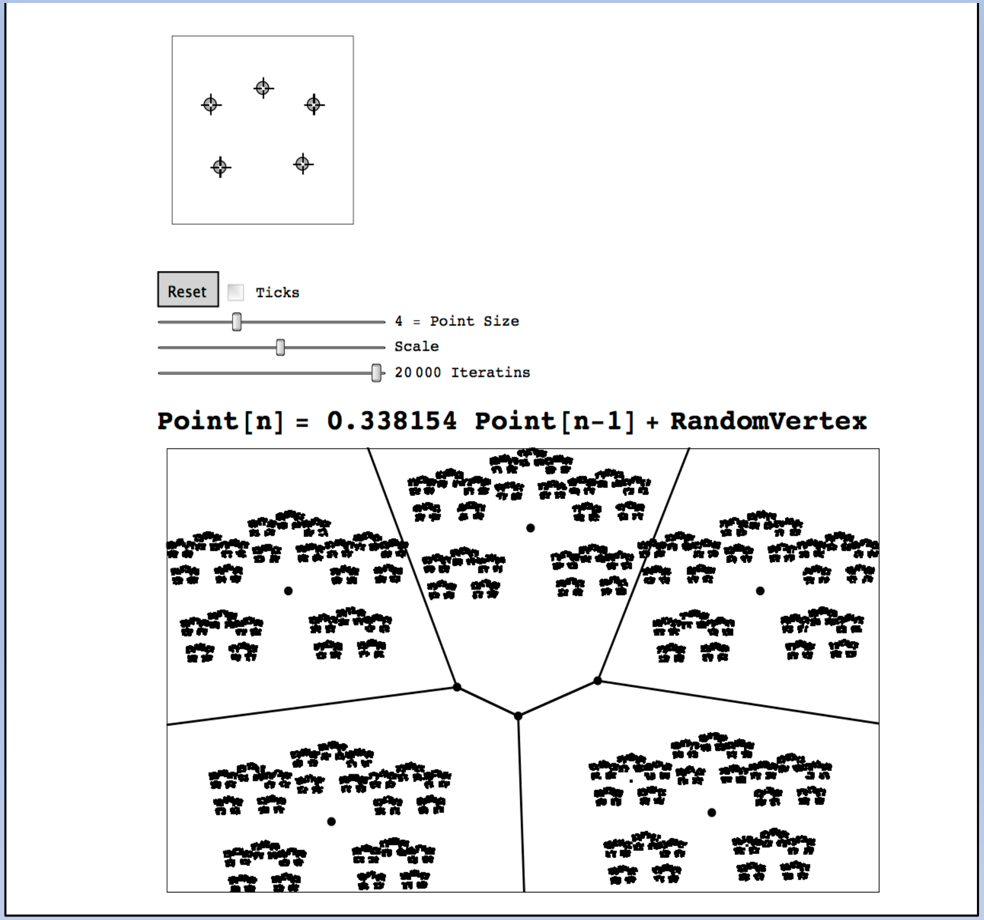
From Random to Order





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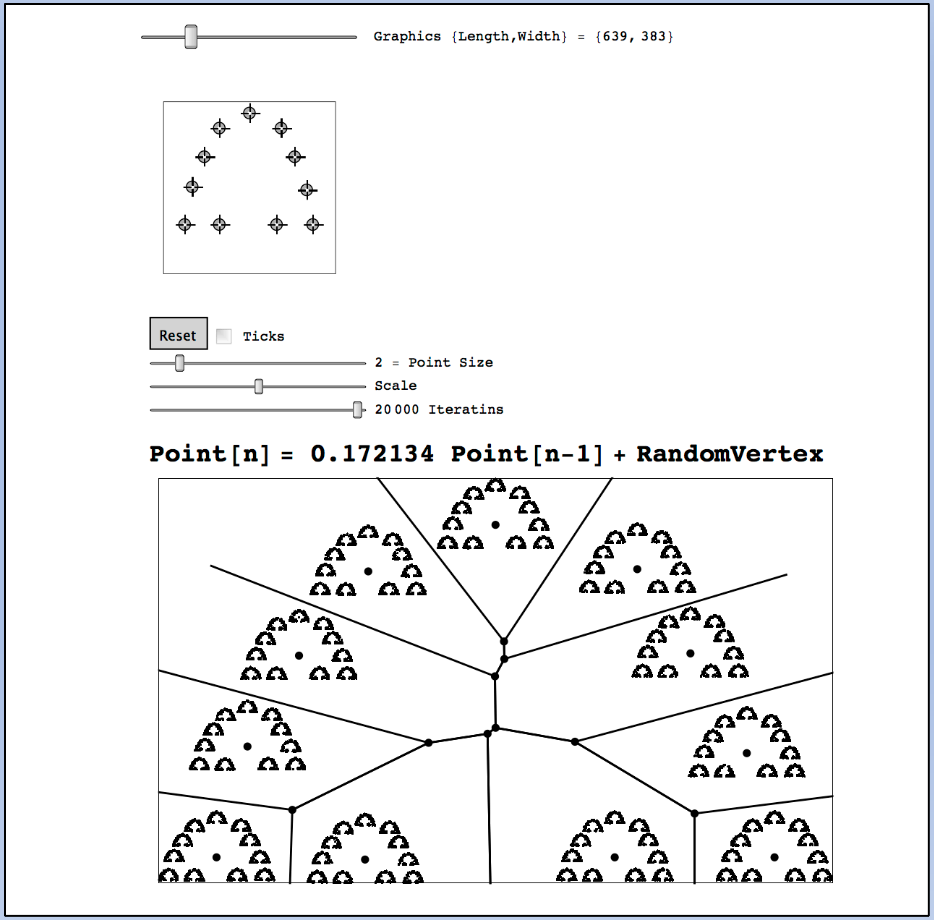
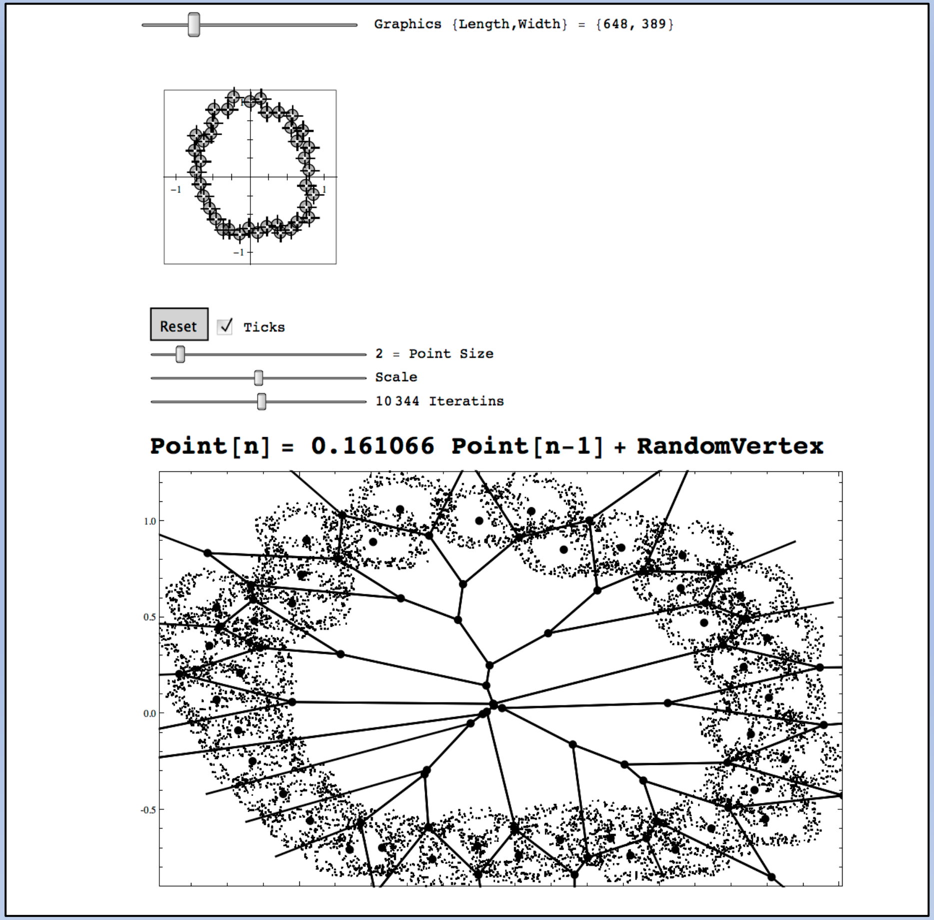
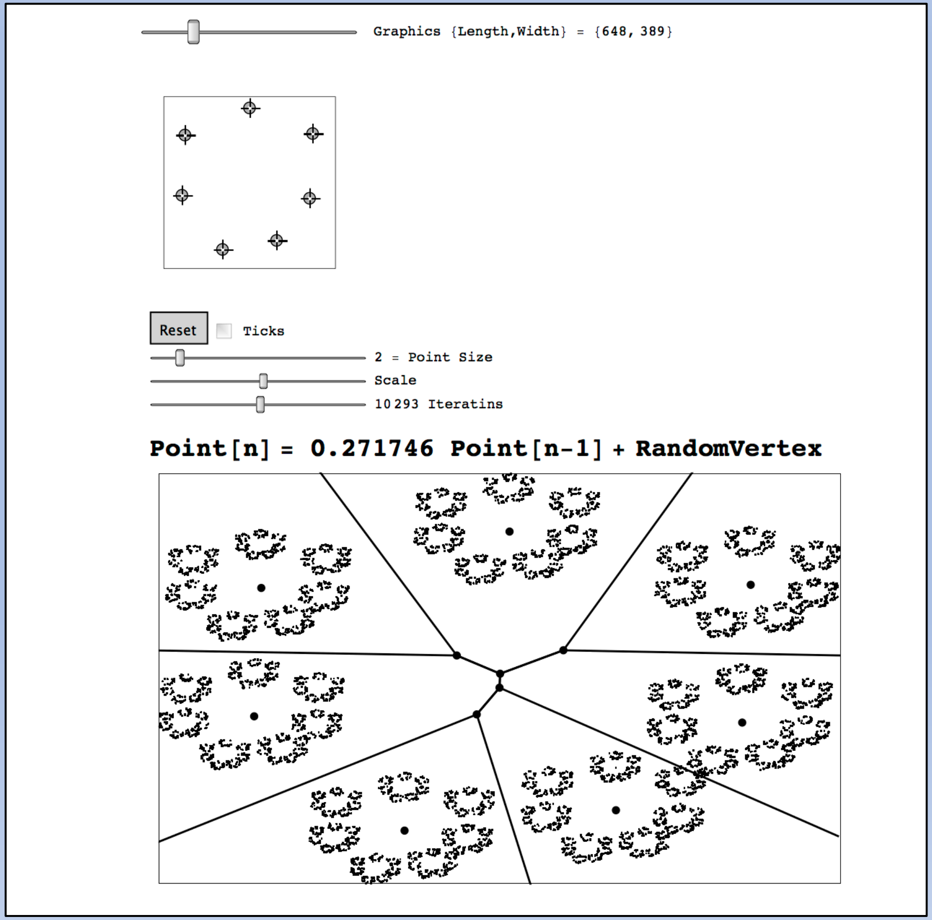
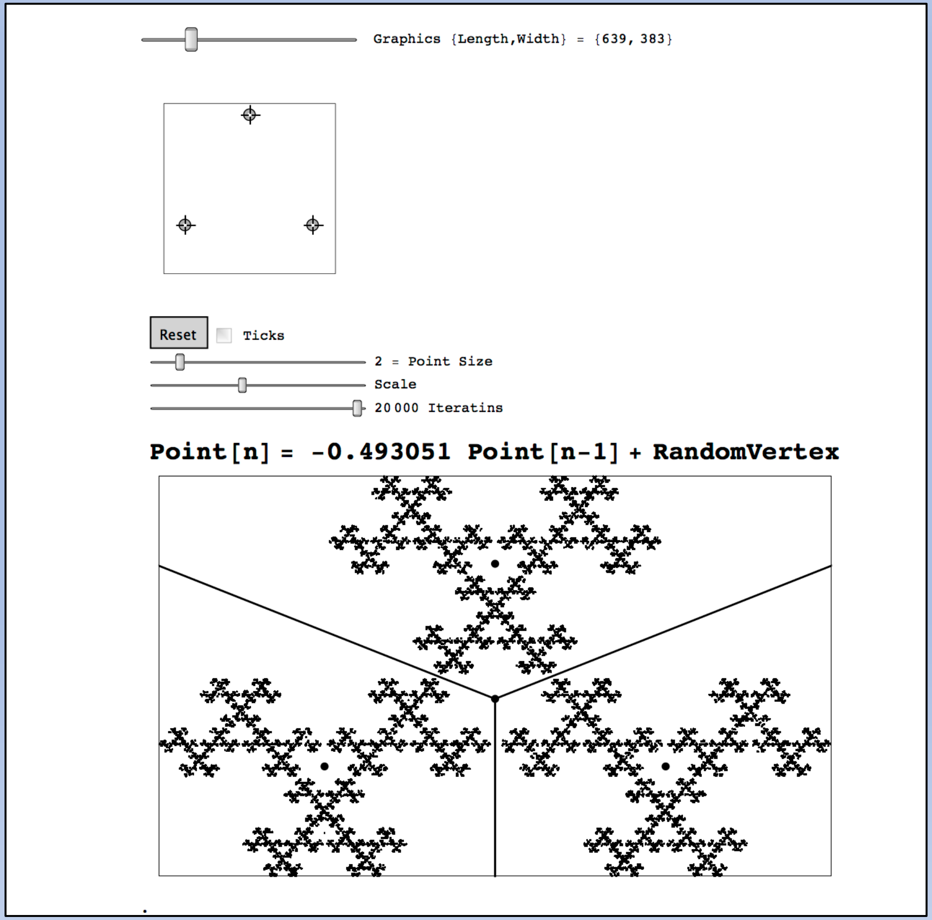
More Patterns





Changing the sign (+/-)





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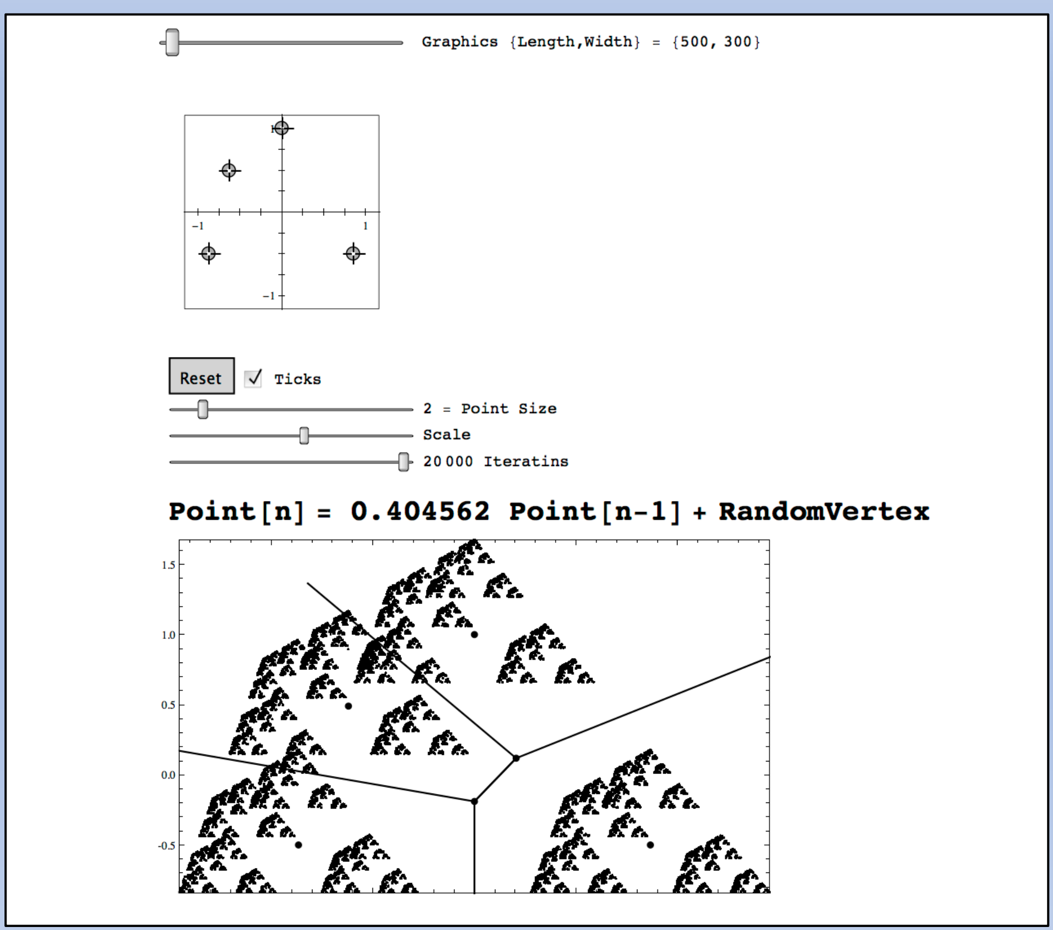
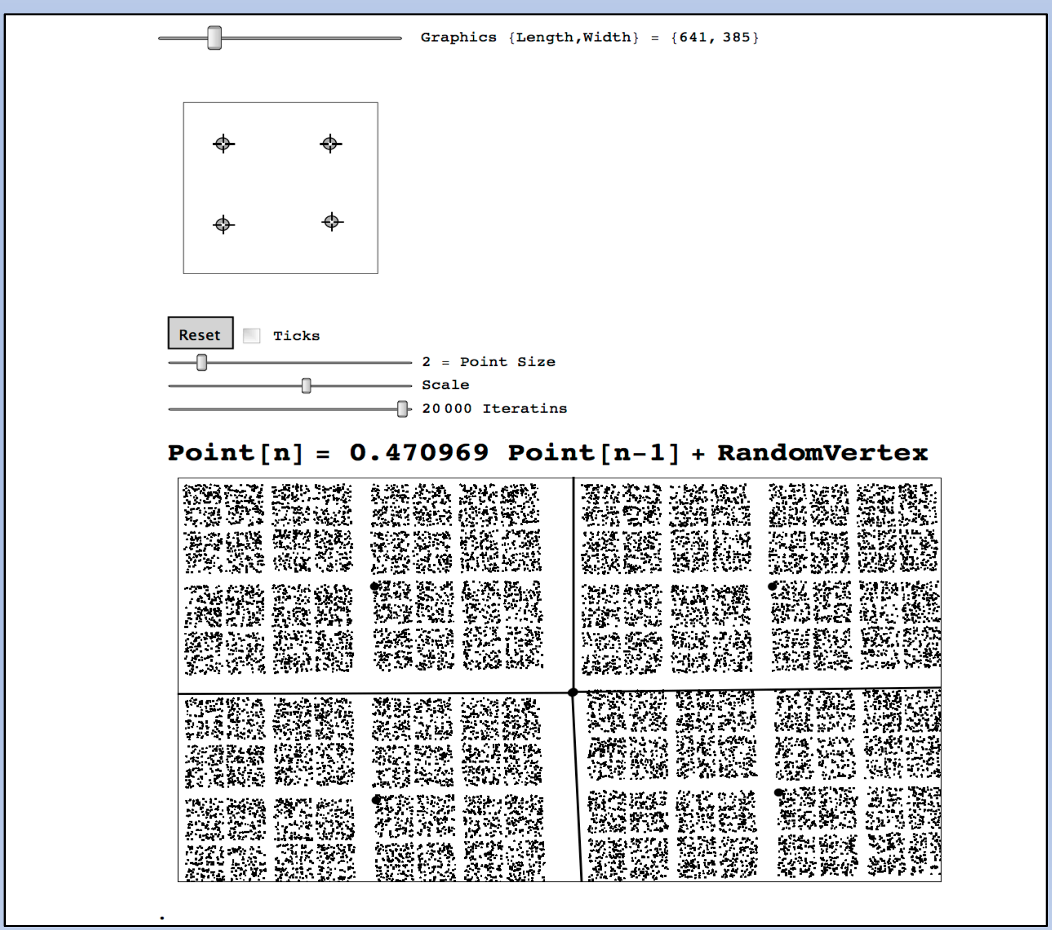
Some differing 4-vertex patterns





Some of the references

- Stigmergy:
  - Lemmens and Tuyls (2010) suggested stigmergy for routing protocols issues. Masoumi and Meybodi (2011) showed relationship of shared information to stigmergy.
- Network Topology:
  - Kleinberg, et al. (2004) showed topology affects network failures as well as attack successes.
- Fractal Traffic Self-organizing:
  - Paxson and Floyd (1995).